REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
11/16/07	Final Report	10/1/03 - 3/31/07

4. TITLE AND SUBTITLE

Shallow Water MCM and ASW Using Off-Board, Autonomous Sensor Networks and Multistatic, Time-Reversal Acoustics

5a. CONTRACT NUMBER

5b. GRANT NUMBER

N00014-04-1-0012

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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Arlington, VA 22217
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10. SPONSOR/MONITOR'S ACRONYM(S)

ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This was a joint project with MIT, Henrik Schmidt et al (separate ONR proposal) and SACLANTCEN (Stevenson and Jensen). The long term goals are to develop environmentally adaptive bi- and multi-static sonar concepts for autonomous off-board sensor networks for the detection and classification of proud, buried and waterborne targets in shallow water. SACLANTCEN provided three weeks of simultaneous sea time for both the R/V Alliance and R/V Leonardo during July 2004. MPL'S main contribution was to develop and test signal processing algorithms.

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16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
unclassified	unclassified	unclassified	None	7	Anne J. Footer / 858-534-1802

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Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

FINAL REPORT: N00014-04-1-0012

SHALLOW WATER MCM AND ASW USING OFF-BOARD, AUTONOMOUS SENSOR NETWORKS AND MULTISTATIC, TIME-REVERSAL ACOUSTICS.

Shallow-Water Autonomous Mine Sensing Initiative (SWAMSI)

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OVERVIEW

This was a joint project with MIT, Henrik Schmidt et al (separate ONR proposal) and SACLANTCEN (Stevenson and Jensen). The long term goals are to develop environmentally adaptive bi- and multi-static sonar concepts for autonomous off-board sensor networks for the detection and classification of proud, buried and waterborne targets in shallow water. SACLANTCEN provided three weeks of simultaneous sea time for both the R/V Alliance and R/V Leonardo during July 2004. MPL'S main contribution was to develop and test signal processing algorithms.

OBJECTIVES

The objective of the research proposed was to combine the results of two ONR sponsored SACLANTCEN Joint Research Projects (JRP), the GOATS (Generic Oceanographic Array Technology Sonar) multistatic MCM initiative led by MIT, and the FAF (Focused Acoustic Fields) time reversal initiative, led by MPL, into a new, environmentally adaptive, multistatic sonar concept for concurrent detection and classification of proud, buried and waterborne targets in shallow water, using off-board autonomous sensing platforms in conjunction with organic, on-board sonar resources. The research was to develop a comprehensive System Modeling and Simulation framework which will be used for performance prediction and experiment planning. Concept demonstration was to be performed through a FY04 field experiment conducted jointly by the three organizations.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
16 NOV 2007	**Final Report**	**01-10-2003 to 31-03-2007**

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	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Hee Chun Song; Peter Gerstoft; William Kuperman; William Hogkiss**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Marine Physical Laboratory,Scripps Institution of Oceanography/University of California, San Diego,291 Rosecrans St.,San Diego,CA,92106**	8. PERFORMING ORGANIZATION REPORT NUMBER **MPL TM-**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **, Office of Naval Research, Ballston Centre Tower One, 800 N. Quincy Street, Arlington, VA, 22217**	10. SPONSOR/MONITOR'S ACRONYM(S) **ONR**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

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Approved for public release; distribution unlimited

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unclassified	**unclassified**	**unclassified**	**2**	**7**	

SONAR CONCEPT

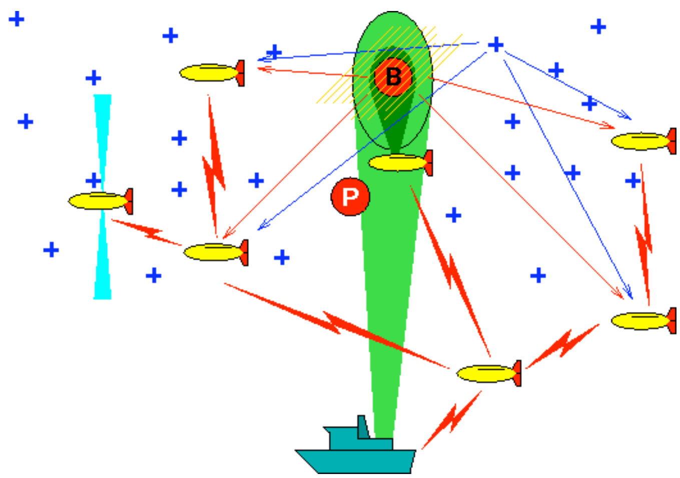


Figure 1. Multistatic, low-frequency sonar concept for concurrent detection and classification of proud and buried targets in shallow water, using off-board, autonomous multi-static sonar platforms in conjunction with organic on-board sonar resources and time-reversal focusing.

The sonar concept, shown schematically in Figure 1, is derived from GOATS, the multi-static, autonomous MCM concept for very shallow water currently being explored by MIT under ONR funding (Codes 321 and 322) in collaboration with SACLANTCEN. It uses a fleet of autonomous off-board platforms to create a wide, combined physical and synthetic aperture for mapping the *spatial and temporal characteristics* of the scattered field produced by the targets in the mid-frequency regime which is rich in target-specific structural responses. The multistatic field characteristics, rather than classical sonar imaging, is then used as the the basis for *concurrent detection and classification*. For insonification the concept would be to use organic, mid-frequency sonar resources on a littoral surface platform, e.g. the SQS53 or a wider-band successor on the Littoral Combat Ship (LCS), in an *environmentally adaptive*, time-reversal mode. Thus, the time-windowed reverberation is used to determine the instantaneous impulse responses from a several kilometer wide, broadside swath of seabed, capturing all the shallow water multipath structure under the current environmental conditions. These inpulse responses are then convolved with the desired waveform, time-reversed and transmitted by the sonar to produce a focused field on the seabed, with the focus scanned over the entire swath, out to ranges of several kilometers. Algorithm development for such use of time reversal reverberation for enhanced sonar performance is currently being explored under ONR funding (Code 321US, Doug Abraham).

A network of autonomous underwater vehicles are used to provide an off-board, multistatic, synthetic receiving array and bi-static SAS concepts, developed under GOATS, to detect, track and classify proud and buried targets in the insonified sonar footprint. Once detection is established, the target coordinates are transmitted back to the surface platform, which will subsequently focus the sound on the target location, while the bistatic platforms adaptively change their path to optimally classify the target from the spatial and temporal characteristics of the bistatic scattering, using adaptive path-planning techniques developed and demonstrated under GOATS. The AUV’s also carry broad-band sources which may be applied for close-in target insonification, using adaptive path-planning and possibly time-reversed target replicas for rapid classification.

APPROACH

MPL's role in this program concerned signal processing for target detection. Hence we were to develop and demonstrate a self-adaptive focusing procedure that required minimial enviornmental information in order to scan the bottom for targets. This was first explored in the laboratory and then subsequently at sea.

RESULTS

Self-adaptive Focusing.

We developed an iterative time reversal procedure to focus on a target/ The first experiments were done in a laboratory. After demonstrating the procedure in the laboratory, data was taken at sea and analysed indicating that the procedure does indeed work. The laboratory setup is shown in Figure 2.

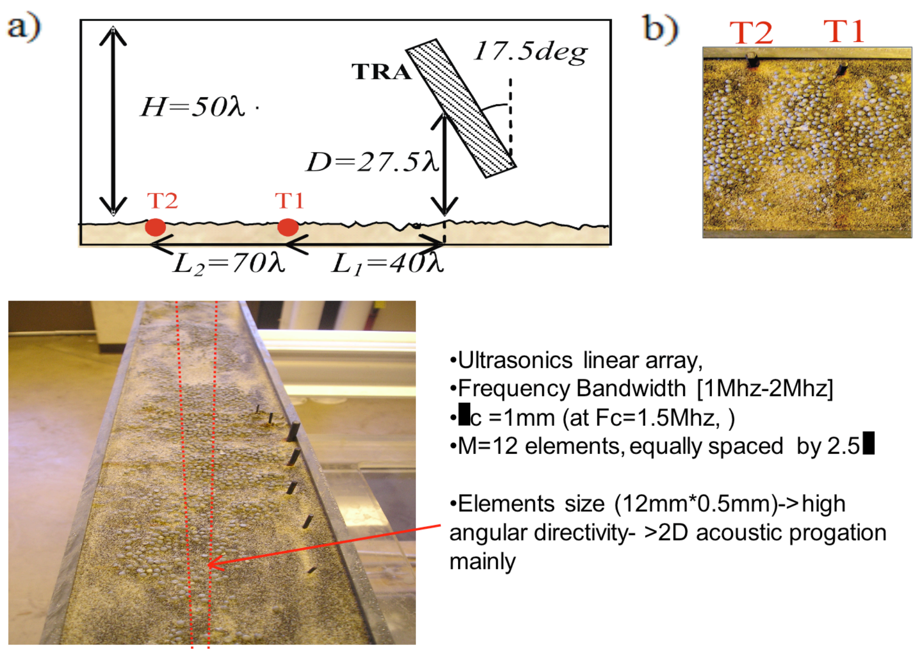


Figure 2. Laboratory setup for ultrasonics experiment to demonstrate iterative time reversal.

The iterative time reversal method shown schematically in Figure 3 was the basis of what was used to construct the reflection maps. However, during practical mapping of the ocean bottom, the TRA is moving between each iteration of the active time-reversal process since it is either being towed by a ship or directly mounted on the ship's hull. This TRA motion is detrimental since the TRA would not retrofocus on the exact same range section on the bottom. We use a passive implementation of the iterative time-reversal process to overcome this issue. This requires the knowledge of the interelement impulse response matrix $\mathbf{K}_{l,m}$ of the M=12 elements of TRA: each element $k_{l,m}(t)$ of the matrix $\mathbf{K}_{l,m}$ is the output of the element number l ($1 \leq l \leq M$), when the input element number m ($1 \leq m \leq M$) is a delta impulse [1,3,4]. In other words, the $k_{l,m}(t)$ signals correspond to the backscattered Green's functions between the l^{th} and m^{th} element of the TRA, including the bottom reverberation, convolved with the probing pulse signal. Then, the time reversal iterations are implemented passively by simply performing correlations of these $k_{l,m}(t)$ signals with the time-gated window of the reverberated signals selected at the previous iterations.

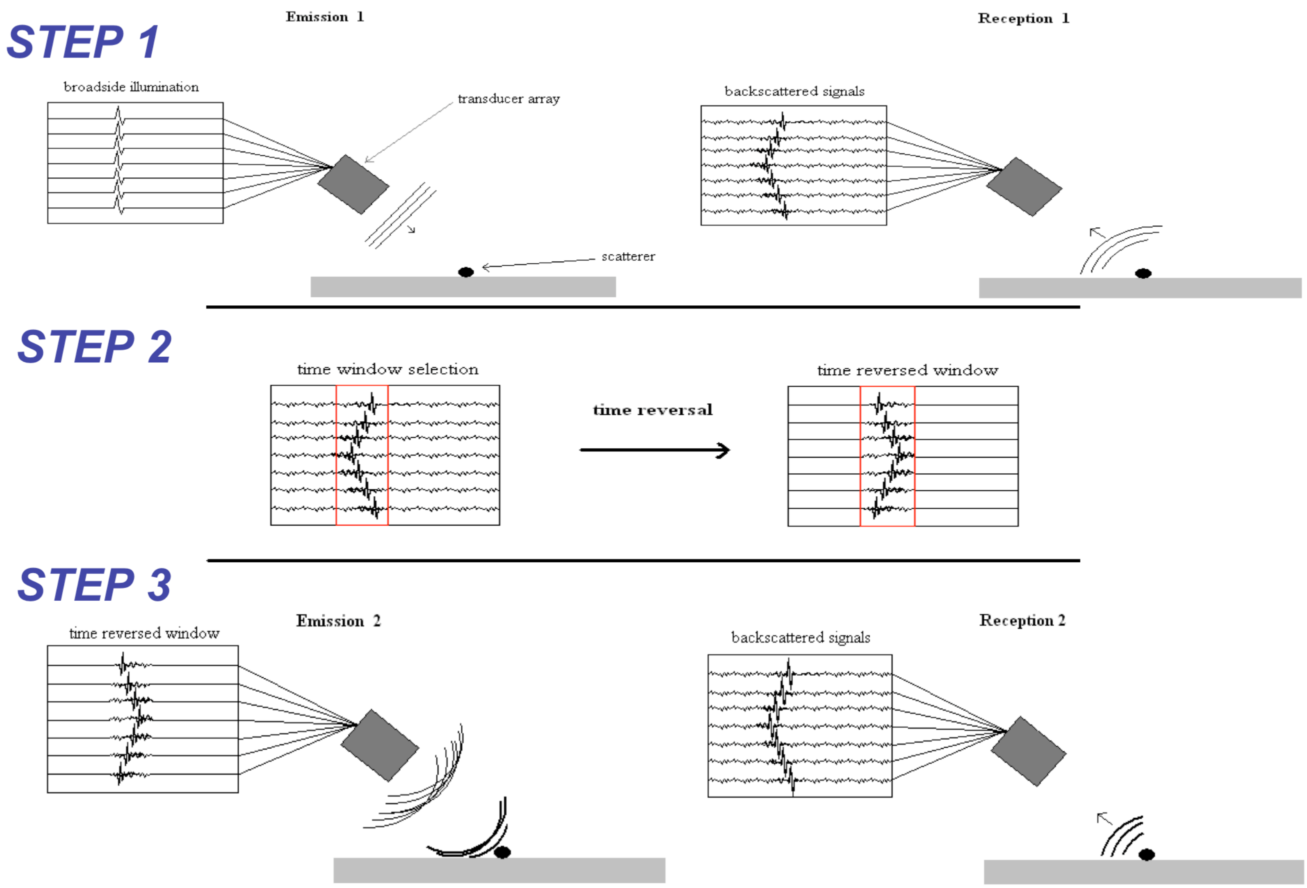


Figure 3. Schematic of iterative time reversal

The interelement impulse response matrix $\mathbf{K}_{l,m}$ can be initially measured by firing successively the same short impulse signal from each individual array element and then recording the backscattered signals on the whole TRA after a round-trip propagation between the TRA and the ocean bottom. To avoid waiting for M succesive reverberation returns to be completed (which might be too long if the TRA is moving), it is possible to record in one shot the matrix $\mathbf{K}_{l,m}$ by probing the waveguide with a set of M orthogonal array beams rather than the individual TRA elements.

For each of the $k_{l,m}(t)$ signals, the recording time t corresponds to the round trip propagation from the TRA to the water-bottom and can thus be converted to an equivalent distance $d=tc_0$ (in wavelengths, λ), where c_0 is the speed of sound in the water tank. The reflectivity maps along the waveguide bottom were constructed using the following steps (see Fig.4):

1. Measure the interelement impulse response $\mathbf{K}_{l,m}$ of the TRA, using a chirp signal. This is the only active part of the process.
2. From $\mathbf{K}_{l,m}$, build passively the M bakcscattered signals $R_m^{(0)}(d)$ (1≤m≤M) issued form a broadside transmission (see Fig. 3)

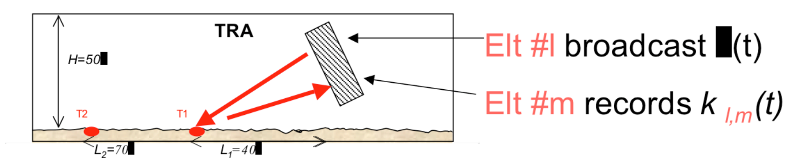
$$R_m^{(0)}(d) = \sum_{l=1}^{M} k_{lm}(d) \qquad (1)$$

3. Select several time-gated windows (of spatial length Δc_0), each associated with a different average range on the bottom L_{av} determined by the center of selected time-gated window (see Fig. 3, for $L_{av}=105\lambda$ where the window length Δ=5μs is delimited by black lines)
4. Perform passively the iterative time-reversal process for each window, by simple correlations (indicated by the symbol $\otimes$) with the elements of $\mathbf{K}_{l,m}$, for a chosen number of iterations N (see Fig. 3.b).

$$R_m^{(i)}(d) = \sum_{l=1}^{M} k_{lm}(d) \otimes R_m^{(i-1)}\left(L_{av} - \frac{\Delta c_0}{2} \le d \le L_{av} + \frac{\Delta c_0}{2}\right) \quad (1 \le i \le N) \; (2)$$

5. Plot the average recorded energy by the TRA, $E_{av}(d,L_{av})$, vs. the illuminated average bottom range L_{av} (see Fig. 1, Fig. 5 and Fig.6). $E_{av}(d,L_{av})$ is computed incoherently, by simply time-aligning the maxima of the envelope of each retrofocused energy signals $R_m^{(N)}(d)$ before doing an incoherent summation.

Step 1: Recording of the inter-element response matrix $\mathbf{K}_{l,m}$
(use set orthogonal signals[redacted]ast acquisition)



$k_{l,m}(d)$ = backscattered Green's function between the l^{th} and m^{th} element of the TRA including the bottom reverberation , convolved with the probing pulse signal.

Step 2: Passive time reversal iterations: use correlations of these $k_{l,m}(t)$ signals with the time-gated window of the reverberated signals computed at the previous iterations $R_m^{(i)}$

$$R_m^{(i)}(d) = \sum_{l=1}^{M} k_{lm}(d) \otimes R_m^{(i-1)}\left(L_{av} - \frac{\delta l}{2} \le d \le L_{av} + \frac{\delta l}{2}\right) \quad (1 \le i \le N)$$

Figure 4. Simplified schematic of the "passive" implementation of iterative time reversal.

An example of laboratory results for a reflectivty map with a target is shown in Figure 5 where four iterations were carried out.

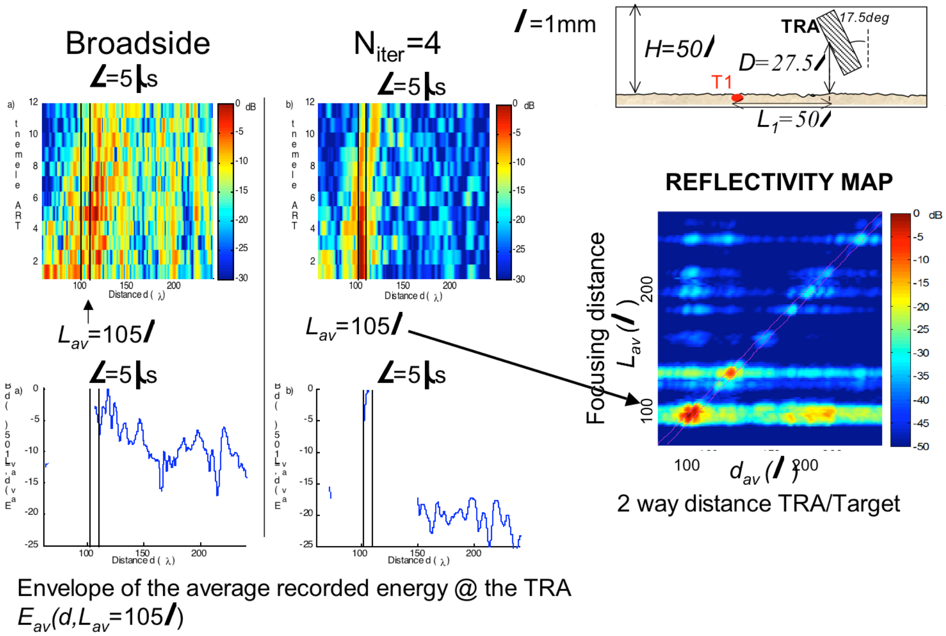


Figure 5 Ultrasonic Laboratory results indicating target is acquired by a self-adaptive process.

At-Sea experimental results

Among the arrays deployed in the FAF04 experiment was the "billboard" arrays shown in Figure. 6 .

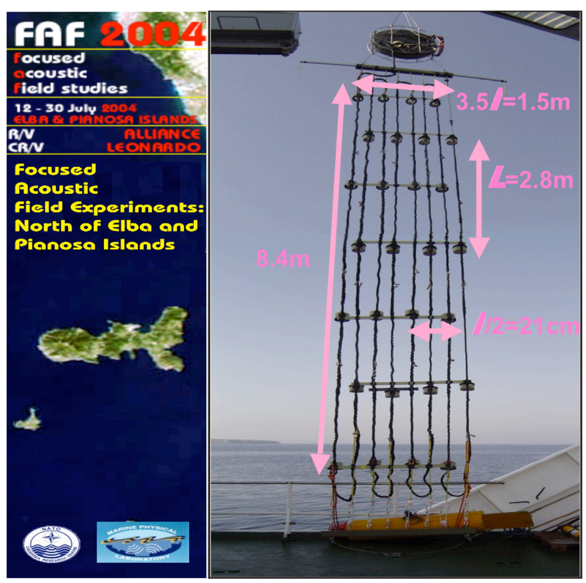


Figure 6: Planar array used in FAF04

An example of results obtained with the Billoboard array are shown in Figure 7 in which there is also a comparision with a noniterative result and a broadside non adaptive result. Clearly, the iterative TR result inhances the target in the reflectivity map.

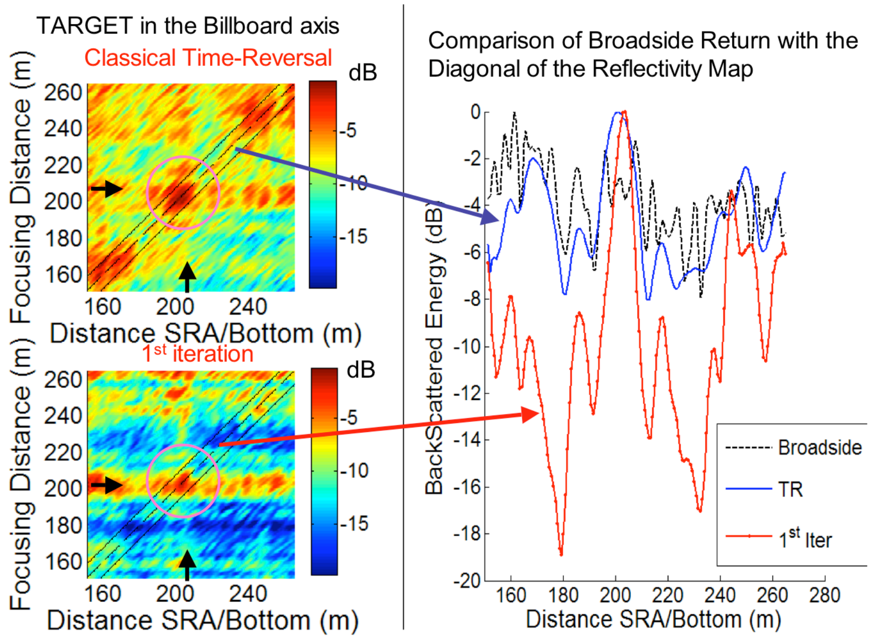


Figure 7. Experimental results for an at-sea reflectivty map showing target detection.

SUMMARY

The results of our research was reported in the publications below.

1. K.G. Sabra, P. Roux and W. A. Kuperman, "Detection of buried targets with passive iterative time reversal processing" in the proceedings of the conference on "The application of recent advances in underwater detection and survey techniques to underwater archeology". Edited by T. Akal, R.D Ballard and G.F. Bass. Bodrum, Turkey, May 2004, pp 199-206.
2. K.G. Sabra, P. Roux, H. C. Song, W. S. Hodgkiss, W. A. Kuperman, T. Akal and M. Stevenson, "Experimental demonstration of time reversed reverberation focusing in a rough waveguide. Application to target detection", J. Acoust. Soc. Am. 120, 1305-1314, (2006).